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Time-dependent Response of Carbon Fibre/Epoxy Composites

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and J.F. Williams

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W.K. Chiu[1], S.C. Galea, R. Jones[1], and J.F. Williams[2]

Airframes and Engines Division
Aeronautical and Maritime Research Laboratory

DSTO-TR-0248

ABSTRACT

In order to achieve optimum design of composite structures and bonded composite joints a full understanding of the fundamental non-linear mechanical behaviour of composite materials and the adhesive systems is required. The time-dependent behaviour of the adhesive systems is reasonably well documented, and has to some degree been accounted for in the design of bonded joints. However this is not the case for matrix materials in carbon fibre/epoxy resin systems. Whilst it is known that matrix-dominated behaviour of composites is highly non-linear, even at room temperature, this is often neglected in the design procedure.

This report presents a study on the non-linear behaviour of a composite material and focuses on the shear behaviour of the carbon fibre/epoxy resin system used in the F/A-18, viz., AS4/3501-6.

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Time-dependent Response of Carbon Fibre/Epoxy Composites

EXECUTIVE SUMMARY

In order to achieve the best possible design of composite structures and bonded composite joints it is important that the behaviour of the composite and the adhesive is fully understood. This report contains experimental results for the composite carbon fibre/epoxy resin system used extensively in the F/A-18 aircraft. These results enable a better understanding of the complex behaviour of these composites and will be used in finite element analysis of composite structures and composite bonded joints to enable greater accuracy in predicting the stresses and strains in the composite.

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Dr Chiu graduated from the University of Western Australia in 1987 with a Bachelor of Engineering (Mechanical) degree with first class honours. In 1991, he received his Doctor of Philosophy (Engineering) with Outstanding Distinction. He was appointed as a Research Scientist in from 1991 to 1994 with the Aeronautical Research Laboratory, Aircraft Structures Division. Dr Chiu is currently a Senior Lecturer at Monash University, Department of Mechanical Engineering. He is currently involved with a variety of projects ranging from fundamental research to industrial research. The main thrust of his research projects are in the area of composite materials, computational and experimental mechanics.

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Dr Galea graduated in 1980 with a Bachelor of Engineering (Mech) from the University of Queensland with first class honours and in 1983, he received a Masters of Engineering Science. He commenced employment with the Aeronautical Research Laboratory in 1983. In 1985 he commenced studies at the Institute of Sound and Vibration Research, University of Southampton, UK and received his Doctor of Philosophy from the University of Southampton in 1989. Dr Galea was appointed a Research Scientist in 1990 and Senior Research Scientist in 1992. Since 1990 Dr Galea has been working in the areas of composite structures, computational and experimental mechanics. He is currently managing tasks related to repairing aircraft structures with acoustic fatigue cracking and smart repair systems for aircraft structures, at the Aeronautical and Maritime Research Laboratory. His other areas of research include bolted and bonded composite joints.

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Contents

1. Introduction

The increasing use of composite materials in load bearing structures requires an understanding of the fundamental mechanical behaviour of composite materials (eg. AS4/3501 AS4 carbon fibre system and 3501 thermoset matrix). Whilst it is known that the matrix materials in carbon fibre/epoxy are often time-dependent, even at room temperature, this non-linear behaviour is often neglected in design procedures.

The matrix materials found in most composite materials are epoxy based. Recent studies by Chiu et al, (1994a) showed that FM73, a rubber toughened epoxy, is strongly non-linear in time at room temperature. In particular, during strain holds, significant stress relaxation occurs. This phenomena can be interpreted as a degradation mechanism in the epoxy as it represents a irreversible dissipation of elastic energy. The behaviour of this epoxy under elevated temperature was subsequently reported by Chiu et al, (1994b). At elevated temperatures, time-dependencies of the epoxy were reported to be even more significant. Since the majority of composite materials are made using epoxy resins, it is therefore important that behaviour of the matrix in the confinement of the carbon fibre be characterised.

Fibre reinforced plastics like AS4/3501 can be found in various components of modern civilian and military aircraft (eg. F/A 18 in the Royal Australian Air Force). Structures made from this composite material are essentially designed such that the fibres are oriented in the principal directions of the load. However, the loads in aircraft structures are often complex with combinations of unidirectional and shear loading. Under these circumstances, the matrix material will now act to transfer and carry this shear loading. Similarly, changes in the "joint" geometry can result in matrix dominated interlaminar shearing forces. This has been recognised to be one of the causes of the disbonding of the structural reinforcement of the F111C wing pivot fitting (Molent et al, 1992 and Molent, 1988).

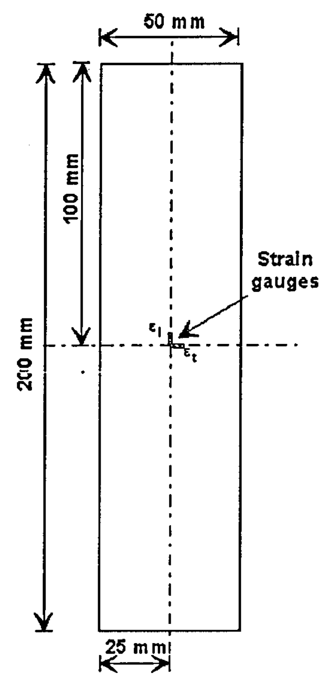
It is therefore important to understand the non-linear effects of composite materials and structures if optimal design of any structure is to be undertaken. This paper presents one such study into the non-linear behaviour of a composite material, AS4/3501-6. Particular attention is focussed on the shear behaviour of the epoxy used as matrix material. This paper will report on;

- The effects of strain rate on the stress/strain behaviour.
- The effects of cyclic loading at various strain rates.
- Strain holds to demonstrate the stress relaxation phenomena.
- Creep experiments performed with load hold experiments.

Similar experiments were also reported by Gates, (1991) where the rate dependent behaviour of advanced composites was studied. However, Gates used a different fibre matrix system (Hercules IM7 fibre and Amoco 8320 matrix, a thermoplastic material). Significant rate dependent behaviour of this matrix material was reported.

2. Test Specimens and Procedures

The geometry of the test specimen is shown in Figure 1 and is nominally 200 mm long by 50 mm wide and 6.5 mm thick. The specimen test section is 115 mm long by 50 mm wide. This specimen was manufactured from a large panel made from AS4/3501 carbon fibre/epoxy. The layup of the panel is $[(\pm 45)_{12}]_s$. As reported by Chiu et al, (1994a), it is essential that the testing of the mechanical behaviour of the epoxy be performed under local strain control. Repeatable results can only be obtained using this testing procedure. As a result, strain gauges located in the centre of the test coupon provided the local strain values and, more importantly, the signal to the strain controller of the Instron testing machine in order to achieve strain rate control. An Instron servo-hydraulic test machine is used for this test program.



48 ply laminate $[(\pm 45)_{12}]_{sym}$

Figure 1: *Geometry of test specimen.*

The tests were performed at room temperature (25-19°C) and at a variety of strain rates, ranging from a slow 0.00001 /sec to the machine maximum of 0.152 /sec. These tests consisted of loading the specimen to a nominal shear strain of 17,000 $\mu\varepsilon$ and then applying a triangular cyclic loading of approximately 10,000 ± 7,000 $\mu\varepsilon$ for a number of cycles. During the stress relaxation tests, the strain was held at a pre-determined value. Table 1 indicates the test condition for each specimen tested.

During the load hold (creep) tests, specimens were loaded at a constant load rate of 1.1 kN/sec and load holds were applied at load levels where non-linearity was observed in the monotonic tests described above. Table 2 indicates the test condition for each specimen tested.

Table 1: List of specimen numbers with the corresponding test condition for the strain control tests.

Spec no.	Strain rate (/sec)	Test type	Spec no.	Strain rate (/sec)	Test type
B-24	0.00001	0.01±0.007 - 15 cycles	B-22	0.152	0.01±0.007 - 15 cycles
B-15	0.00017	0.01±0.007 - 1 cycle	B-01t4	0.000108	Stress relax - strain hold at 0.02
B-18	0.00014	0.01±0.007 - 15 cycles	B-05	0.135	Stress relax - strain hold at 0.029
B-17	0.0188	0.01±0.007 - 15 cycles			

Table 2: List of specimen numbers with the corresponding test condition for the load control tests.

Spec no.	Load rate (kN/sec)	Test type
B-11	1.1 (0.00013)+	Creep - load hold at 60 MPa
B-12	1.1 (0.00017)+	Creep - load hold at 70 MPa

+ Approximate strain rate (/sec)

The load and strain values obtained from the Instron test machine were acquired by either a Macintosh II, the ISGAR IBM compatible and the AMLAB data acquisition systems. The load was converted to shear stress (τ), using

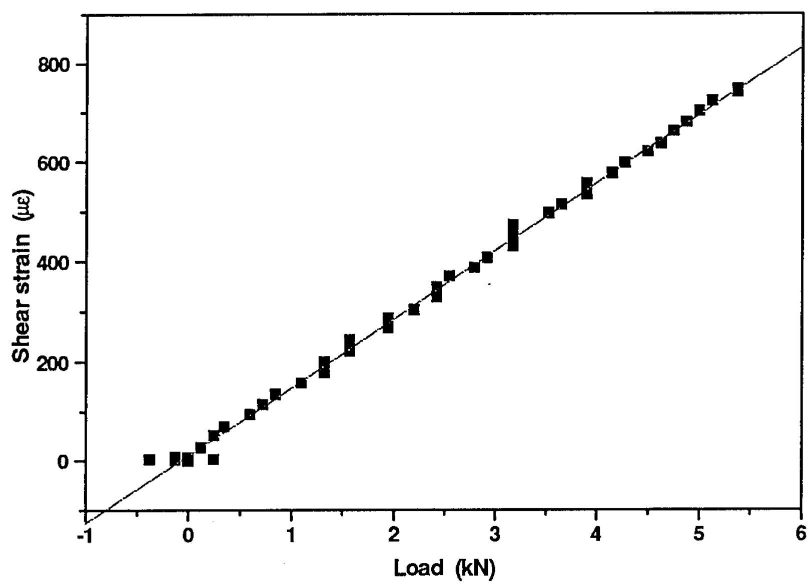
$$\tau = P/(2\,w\,t) \qquad (1)$$

where P is the applied load, w is the specimen width and t is the specimen thickness. The shear strain (γ) was obtained from the strain gauge rosette located on the test specimen, i.e.

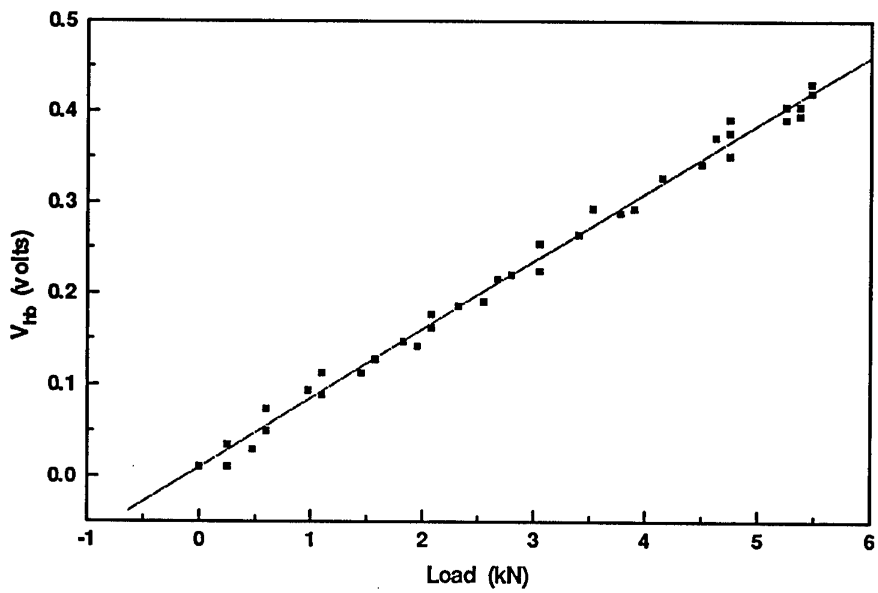
$$\gamma = (\varepsilon_l - \varepsilon_t)/2 \qquad (2)$$

where ε_l and ε_t are the direct strains measured in the longitudinal and transverse directions, respectively, as illustrated in Figure 1.

For the testing machine to run in strain control, the strain gauges were wired-up in a Wheatstone half bridge arrangement such that the output voltage from the bridge was essentially (ε_l - ε_t). This voltage was then the input into the testing machine and used as the feedback signal for the strain control tests. In order to calibrate this voltage, i.e. to determine the exact relation between this voltage and the shear strain on the specimen two calibration runs were require. The first was to load the specimen to 5 kN, in load control, measuring load, ε_l and ε_t. The second run was in strain control measuring the variation of load with the half bridge voltage (designated here as V_{hb}). These runs produced plots of (a) shear strain versus load and (b) V_{hb} versus load, respectively. Typical plots are given in Figure 2. This then allowed the determination of the relation between V_{hb} and measured shear strain, as shown in Appendix A.



(a)



(b)

Figure 2: ***Typical calibration plots for the half bridge signal. (a) shear strain (γ) versus load (P) and (b) half bridge voltage (V_{hb}) versus load (P) (specimen B-22).***

3. Results and Discussions

Figure 3 shows a typical plot of shear strain against time during a test. Repeatability of test results is illustrated in Figure 4, where two specimens were loaded at nominally similar strain rates, viz. B-18 and B-15 at strain rates of 0.00014 and 0.00017 /sec, respectively. This figure shows the excellent repeatability achieved when the specimens are tested under local (shear) strain control.

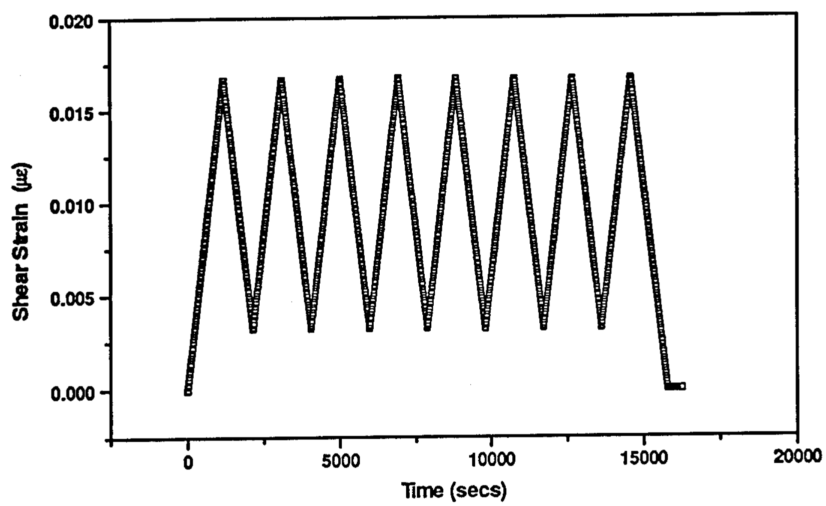


Figure 3: *Typical variation of shear strain with time during cyclic load tests under strain control (specimen B-24).*

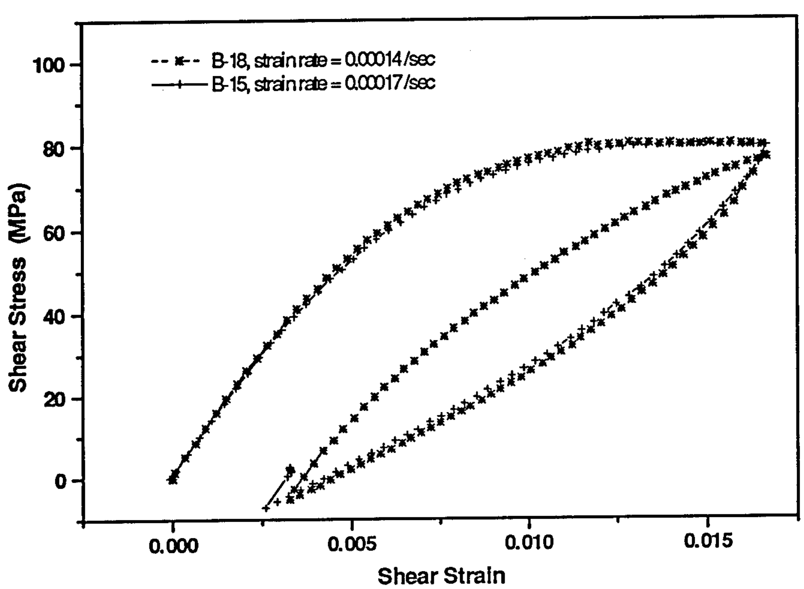


Figure 4: *Shear stress / shear strain behaviour of carbon fibre / epoxy resin system AS4/3501-6 for two test specimens at similar strain rates.*

The stress / strain behaviour of the carbon fibre/epoxy at various strain rates is shown in Figure 5. These curves demonstrate the dependencies of the stress / strain behaviour of the composite material on strain rates, where at high shear strain levels, the value of shear stress in the material may vary by up to 20% depending on the strain rate applied. For a general structure, in the vicinity where local geometry changes occur, the local strain field changes rapidly. This can also be interpreted as a region of highly variant strain rates. Therefore, material in this location can follow a different stress / strain curve depending on its strain rate. This phenomena was studied numerically by Jones et al, (1993) where it was shown that under these circumstances, analysis of the structure using traditional single stress / strain curve can result in gross errors in the estimation of the stress / strain values. A more accurate assessment of the structure can only be attained when the time-dependency of the material is incorporated in the analysis.

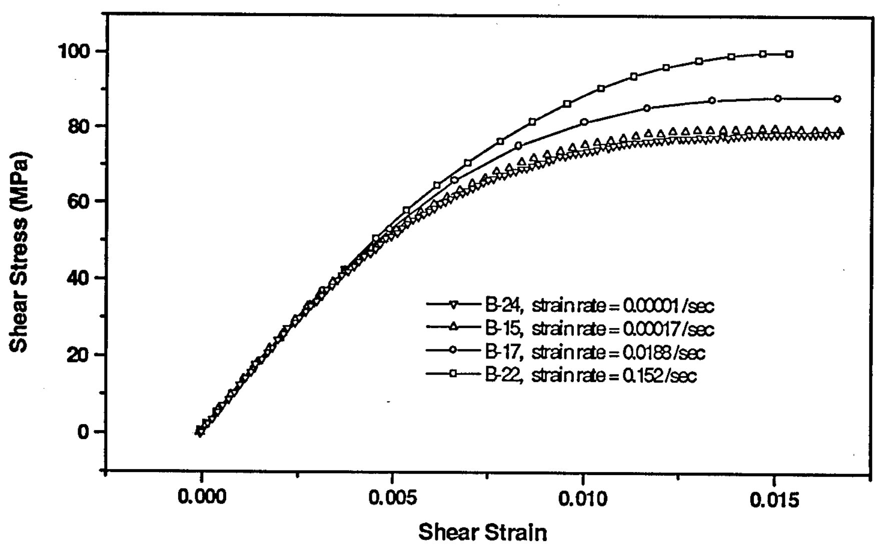
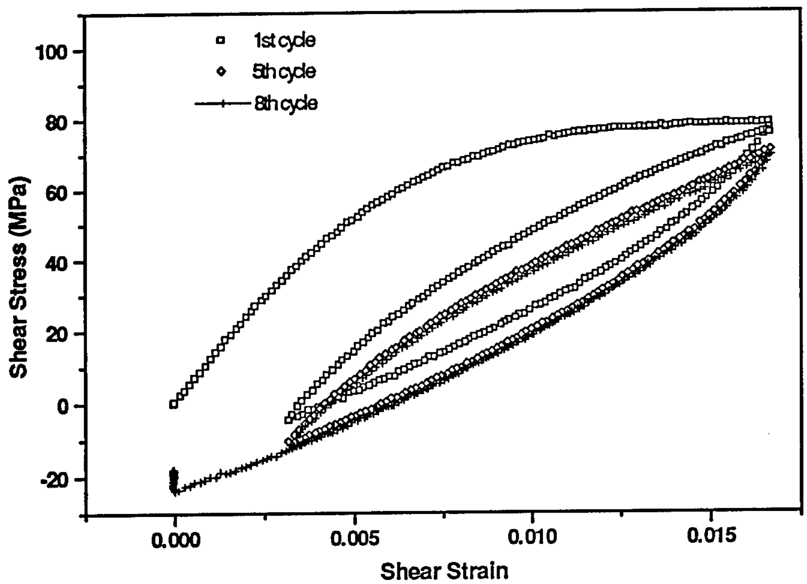
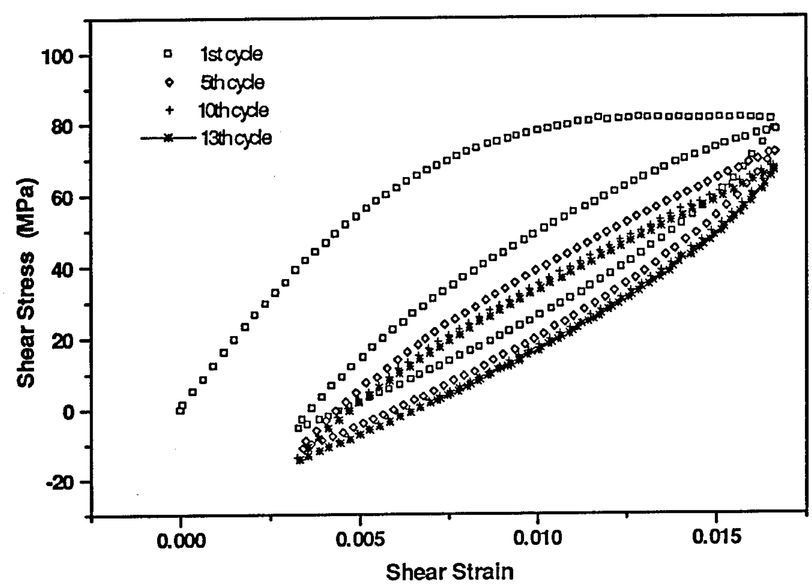


Figure 5: ***Shear stress / shear strain behaviour of carbon fibre / epoxy resin system AS4/3501-6 at various strain rates.***

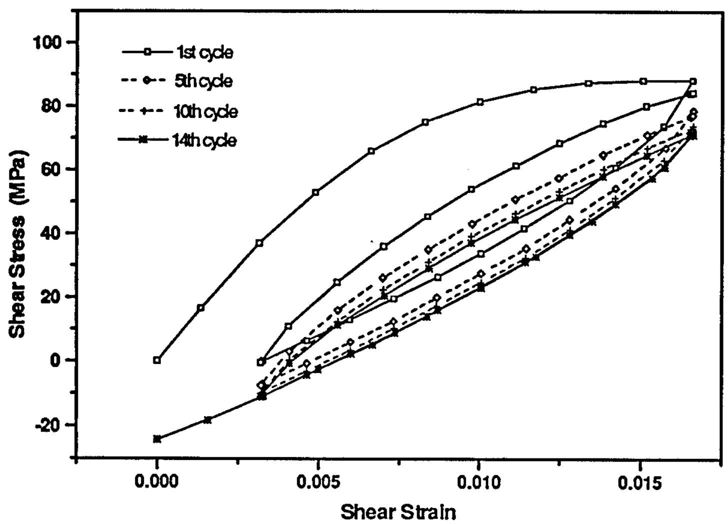
The cyclic load results for specimens B-24, B-18, B-17 and B22 are shown in Figure 6. Figure 6(a) shows that the hysteresis curve, for a shear strain rate of 0.00001 /sec has saturated at about the 5th cycle. Specimens loaded at higher rates require a greater number of cycles to reach saturation. Typically for the higher rates, greater than 0.00014 /sec, about 10 cycles are required before saturation is achieved.


1st cycle
5th cycle
8th cycle
Shear Stress (MPa)
100
80
60
40
20
0
-20
0.000
0.005
0.010
0.015
Shear Strain

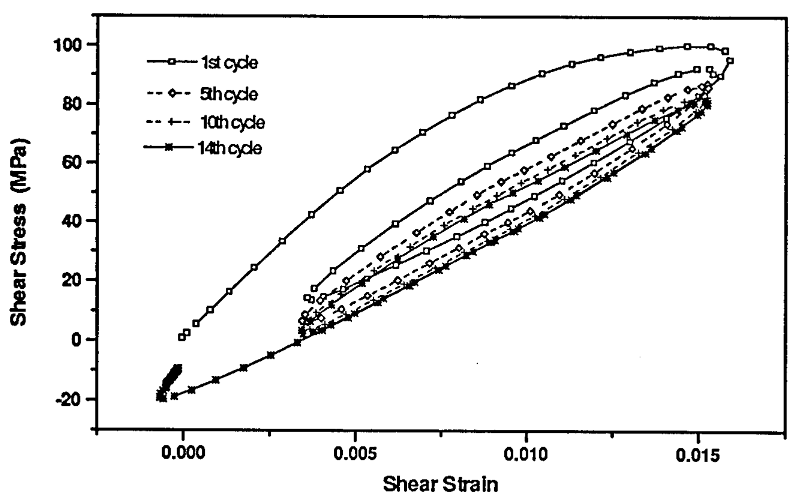
(a)


1st cycle
5th cycle
10th cycle
13th cycle
Shear Stress (MPa)
100
80
60
40
20
0
-20
0.000
0.005
0.010
0.015
Shear Strain

(b)

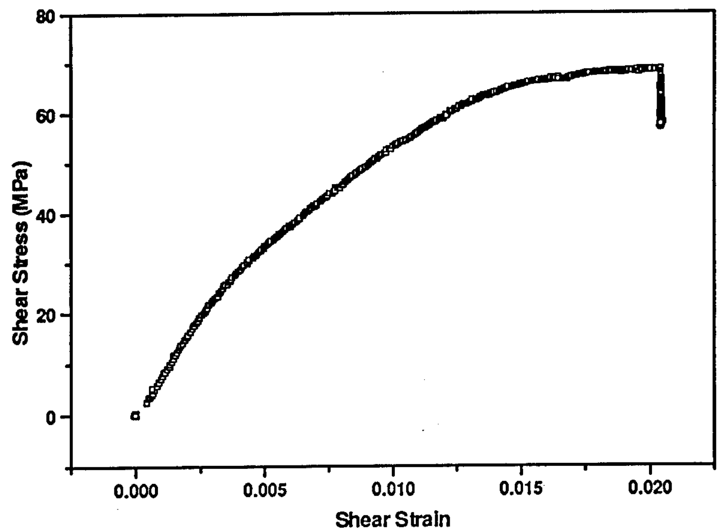


(c)

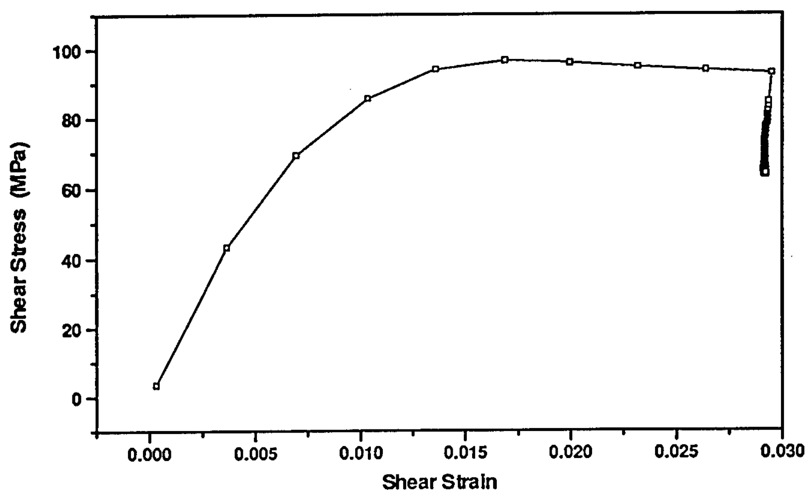


(d)

Figure 6: ***Shear stress / shear strain behaviour of carbon fibre / epoxy resin system AS4/3501-6 under cyclic loading at various strain rates. (a) 0.00001 /sec (B-24), (b) 0.00014 /sec (B-18), (c) 0.0188 /sec (B-17) and (d) 0.152 /sec (B-22).***

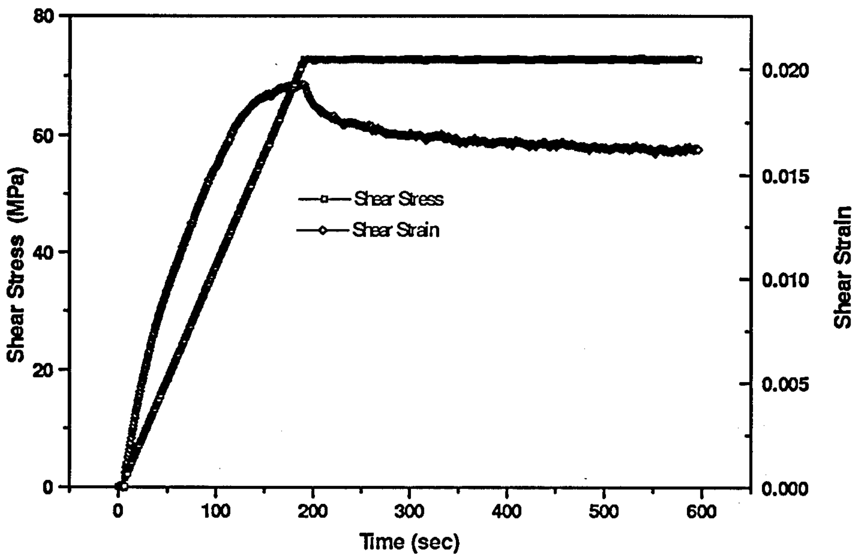


(a)

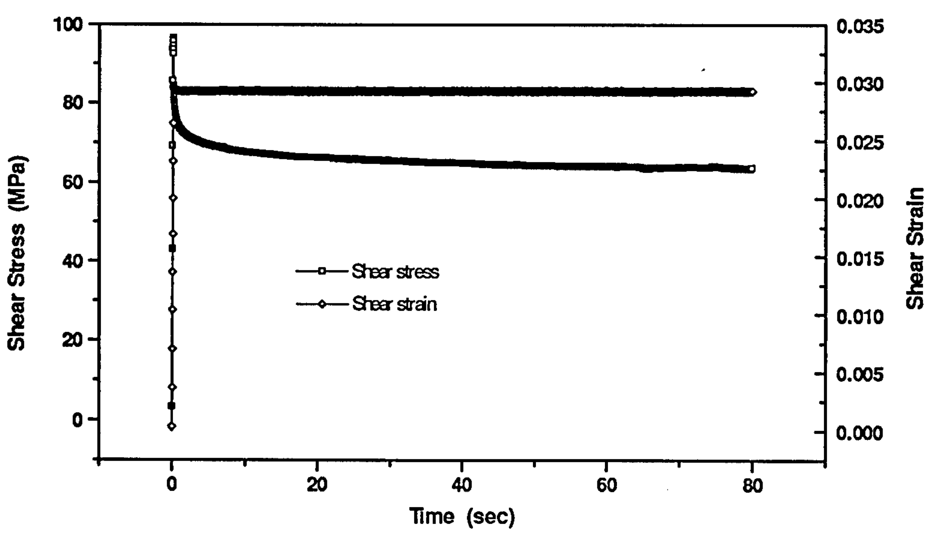


(b)

Figure 7: *Stress relaxation behaviour of carbon fibre / epoxy resin system AS4/3501-6 at various strain rates.*
(a) 0.000108 /sec (B-01t4) and (b) 0.135 /sec (B-05).



(a)



(b)

Figure 8: ***Temporal stress decay during stress relaxation experiments. (a) 0.000108 /sec (B-01t4) and (b) 0.135 /sec (B-05).***

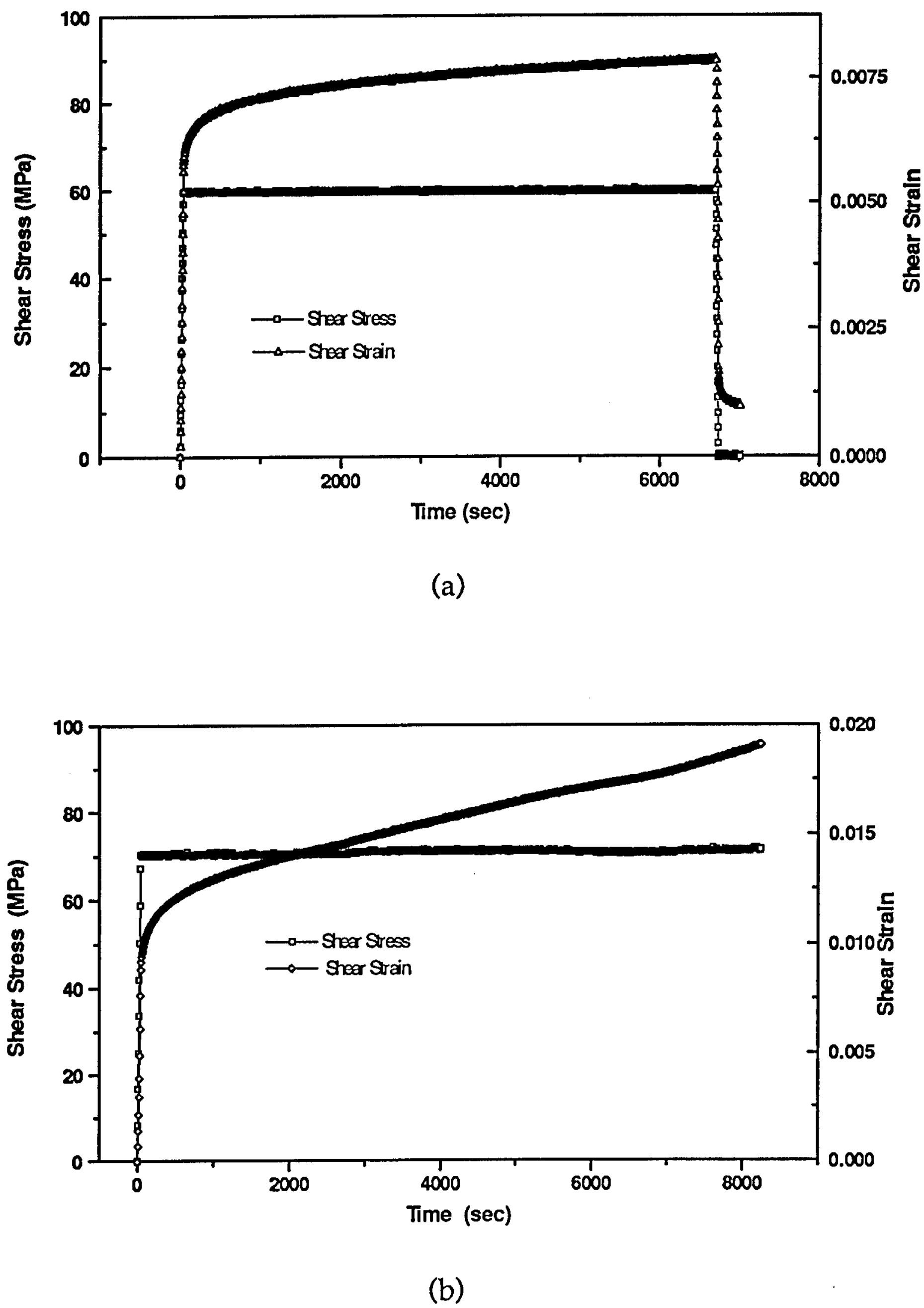


Figure 9: ***Temporal strain development during load holds (creep test) at (a) 60 MPa and (b) 70 MPa.***

The results from the stress relaxation experiments are shown in Figures 7(a) and (b). The temporal stress decay during these experiments are shown in Figures 8(a) and (b). As discussed by Chiu et al (1994), during strain holds, the stress decays to an asymptotic limit. In this case, this limit is approximately 60 MPa. It can be seen that during a strain hold, depending on the initial loading rate, a stress decay of up to 30% can be obtained. Figure 8(b) shows that this 30% drop in shear stress (or load) was attained in less than 5 secs. This demonstrates the highly non-linear behaviour of the matrix material of this particular carbon fibre/epoxy. This stress drop can be interpreted as a degradation of the matrix material as it represents a conversion of elastic energy to irrecoverable energy as the total strain is held at a constant value.

Figures 9(a) and (b) show the creep characteristics of the matrix materials. These figures show that even at room temperature, the matrix exhibits significant time-dependent behaviour. It is expected that the creep rate is dependent on the load at which the test specimen is held at, viz; the higher the load, the higher the creep rate. Creep is of course a reflection of the degradation of the material. The load being held constant (ie. elastic strain is constant) implies that the temporal development of strain contributes directly to the increase in inelastic strain. This may be interpreted as an accumulation of damage in the matrix material.

4. Conclusion

As a result of these experimental findings, the non-linear time-dependent mechanical behaviour of carbon fibre/epoxy has been clearly documented. The rate-dependent stress/strain behaviour of the material is reflected in its rapid rate of stress decay during strain hold (in some cases, 30% in less than 5 sec) and significant creep characteristics. Therefore, this behaviour may have to be taken into account if an accurate assessment of a composite structure is required.

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Appendix A

The table below lists the calibration constants for the specimens reported here. The constants are given by the following equations,

$$V_{hb} = a_1 + a_2 \ P, \qquad A.1$$

$$\gamma = a_3 + a_4 \ P, \qquad A.2$$

$$\gamma = b_1 + b_2 \ V_{hb} \text{ and} \qquad A.3$$

$$V_{hb} = b_3 + b_4 \ \gamma. \qquad A.4$$

Table A.1: Calibration constants relating shear strain to half bridge voltage.

Spec. No.	a_1	a_2	a_3	a_4	b_1	b_2	b_3	b_4 x10-6
22	0.00936	0.07517	10.083	136.8	-6.95	1819.9		549
24	0.01137	0.0955	-18.58	169.1	-38.64	1770.7		565
15	-0.00773	0.06665	-27.35	123.9	-41.7	1859.0		538
18	0.00271	0.0686	10.27	121.4	5.47	1769.7		565
17	-0.00345	0.06672	-1.974	124.7	-1.97	1869.0		535
11	0.00481	0.06489	12.58	116.4	3.95	1793.8		557
12	0.01119	0.06607	25.12	126.5	3.7	1915		522

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S.C. Galea

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20. ABSTRACT In order to achieve optimum design of composite structures and bonded composite joints a full understanding of the fundamental non-linear mechanical behaviour of composite materials and the adhesive systems is required. The time-dependent behaviour of the adhesive systems is reasonably well documented, and has to some degree been accounted for in the design of bonded joints. However this is not the case for matrix materials in carbon fibre/epoxy resin systems. Whilst it is known that matrix-dominated behaviour of composites is highly non-linear, even at room temperature, this is often neglected in the design procedure. This report presents a study on the non-linear behaviour of a composite material and focuses on the shear behaviour of the carbon fibre/epoxy resin system used in the F/A-18, viz., AS4/3501-6.						